U.S. Large Hadron Collider (LHC) Project Lessons Learned

I. U.S. Compact Muon Solenoid (CMS) Project

Key elements that contributed to the success of U.S. CMS include the assignment of adequate contingency, the application of significant engineering design effort at an early stage, and the procurement of major M&S items early in the project.

WBS 1.1 Endcap Muon System- All Cathode Strip Chamber parts were produced in the U.S. to very tight tolerances, and chamber assembly was set up as a factory operation at a number of sites. This paradigm worked very nicely, and allowed us to deliver a large number (396) of very high quality chambers.

WBS 1.2 Hadron Calorimeter- As typical of large projects, the engineering was initially underestimated. However sufficient investment in engineering in the early days of the project allowed us to build the project on schedule with little contingency usage.

WBS 1.3 Trigger and Data Acquisition System- The engineering of the support infrastructure and the interfaces to other subsystems is difficult to properly estimate. This is often due to inadequately prepared or understood multiple boundaries of responsibility in large multi-national collaborations. The DAQ has benefited from using commercial hardware solutions where ever possible and by having a modular design both in hardware and in software. Releasing software to users as early as possible, while a drain on manpower in terms of maintenance, is key in ensuring robust, usable software.

WBS 1.4 Electromagnetic Calorimeter- The rapid progress in electronics technologies needs to be closely tracked.

WBS 1.5 Forward Pixel Tracker- The R&D required for a novel type detector such as this one is hard to estimate. This is especially the case because of the additional constraints such as the availability of radiation hard technologies and the sharing of responsibilities amongst different institutes in a large multinational collaboration. A project like this will benefit to have a lead mechanical and electrical engineer early on who will see through both the R&D and production phase of the project.

WBS 1.6 Common Projects- The U.S. CMS Common Project responsibilities were chosen to match the U.S. construction responsibilities. The HCAL is supported from the barrel yoke, and the EMU chambers are supported from the endcap yoke. The matching of detector and common project responsibilities contributed to the success of both.

WBS 1.7 Project Office- Effort expended in developing a maintainable WBS structure and cost and schedule reporting system were key elements contributing to successful management of the project. The selection of project management software put in the hands of the level-two managers strengthened their ownership of their respective level-two subsystem.

WBS 1.8 Silicon Tracker- U.S. should be involved more directly in component design and fabrication QA in future (e.g. upgrade) CMS tracking systems.

II. U.S. A Toroidal LHC Apparatus (ATLAS) Project

- Specifically define a list of Deliverables in MOUs. Definitions in terms of percentages or levels of effort can keep increasing in cost, as we saw in this project.
- Management Contingency concept worked to keep cost increases down and allowed for optimal management of scope to maximize the U.S. contribution to the detector.
- Do not rely on sole source procurements if possible.
- We never made a visit to a collaborator or a vendor which was not productive – make more trips.
- System engineering (aka Technical Coordination in ATLAS) is critical early in a large Project and should not be underestimated.
- Reviews are useful.

WBS 1.1 Silicon Subsystem - Undergraduate students have been very cost effective doing testing of components after tests have been debugged. The division of labor between institutions was not optimum initially and had to be adjusted over time. More attention to this at an early stage would have been advantageous.

WBS 1.2 TRT Subsystem - System testing should be completely and formally conducted and documented to determine all possible effects of design gas on system components. Gluing operations require more testing and adherence to strict procedures to increase yield and quality.

WBS 1.4 Tile Calorimeter Subsystem- Close cooperation and feedback with vendors, including well-agreed inspection and QA procedures are important for key components. This (well-known) lesson was learned in both positive and negative ways.

WBS 1.10 Technical Coordination - Early establishment and empowerment of an effective Technical Coordination effort is essential for the timely completion of any large-scale project like the ATLAS detector.

III. U.S. LHC Accelerator Project-

The U.S. LHC Accelerator Project was a collaboration among domestic and foreign laboratories requiring research, development and first-of-a-kind fabrication. Cost contingencies ranging from 10% for routine activities to 40% for first-of-a-kind hardware were necessary. Regular, frequent engineering interactions were established early in the project and were a significant factor in the success of the project. An analysis completed at the end of the project suggests the overall contingency rate of 25% established in the beginning of the project was too optimistic, given the above conditions, by 1 to 2%.

WBS 1.1 Interaction Region Components- Ample schedule float and cost contingency is necessary to define and integrate the various components from the varied sources. General performance and geometric requirements were developed early in the project which enabled the laboratories to initiate their design and development efforts, however integration of hardware into the machine was more difficult than anticipated. The detailed integration engineering support needed by CERN was not fully appreciated by the collaborating laboratories, both domestic and foreign, until late in the project. Therefore operational and fit-up details evolved during the project as more attention was placed on integration and installation, resulting in hardware design changes and requests for scope changes that placed a burden on the U.S. Project that often could not be accommodated. As it was not a ‘hardware’ item, it was difficult to add the engineering effort needed into the project scope once the project was underway.

WBS 1.2 RF Straight Section- As with WBS 1.1 effort, changes in some of the details of the design of the machine resulted in changes to the U.S. design. In large international projects such as this, when the efforts of all the laboratories are evolving in parallel, there must be adequate schedule float and budget contingency available to accommodate the effects of design changes.

WBS 1.3 Superconducting Strand and Cable- The superconductor testing originally anticipated specific delivery rates from the cable vendors to CERN from which samples were selected for testing in the U.S. Laboratory. The cable vendors were unable to meet these rates, causing the testing in the U.S. laboratory to fall behind the schedule but still enduring the costs of maintaining infrastructure and skilled personnel.

WBS 1.4 Accelerator Physics- A key component of understanding of the U.S. deliverables and the machine was developed here. European colleagues tend to view this work as ‘scientific’ and there tend to be misunderstandings with respect to the scope of work and why it is included as a project cost.

WBS 1.5 Project Management- The establishment in the U.S. Project of a central project management function was effective in coordinating the requirements and resources for the successful completion of the project. The support of upper management at each laboratory for the project office was crucial in enabling the most effective distribution of DOE resources across the project and to ensure that the project receive the necessary level of priority within each laboratory. The Project Office was highly useful in establishing and maintaining continual communication among the collaborating laboratories.

The original focus of the U.S. Project at inception, and therefore for individual laboratories, was on hardware deliverables which delayed attention to the level of engineering support needed and desired by CERN. Logistics of receiving multiple components for final assembly was not adequately accounted for in schedule float. This also resulted in an underestimate of the schedule and cost required. Installation support was not included in the project baseline and this ultimately has not been perceived well. As opposed to filling the project at inception, as a participating project in a much larger enterprise, it might have been possible to slightly under-subscribe at inception leaving more room for additional work scope as the project developed, though this may have made the project harder to manage during the course of the project.